Overwinter changes to near-surface bulk density, penetration resistance and infiltration rates in compacted soil

Jonathan J. Halvorson[a,*], Lawrence W. Gatto[b], D.K. McCool[c]

[a]USDA-Agricultural Research Service, Appalachian Farming Systems Research Center, Beaver, WV 25813, USA
[b]Geological Sciences Division, Research and Engineering Directorate, US Army Cold Regions Research and Engineering Laboratory, Hanover, NH 03755-1290, USA
[c]USDA-Agricultural Research Service, Land Management and Water Conservation Research Unit, Pullman, WA 99164, USA

Abstract

Previous studies at Yakima Training Center (YTC), in Washington State, suggest freeze-thaw (FT) cycles can ameliorate soil compacted by tracked military vehicles [J. Terramechanics 38 (2001) 133]. However, we know little about the short-term effects of soil freezing over a single winter. We measured bulk density (BD), soil penetration resistance (SPR), and steady-state runoff rates in soil newly tracked by an Abrams tank and in uncompacted soil, before and after a single winter at YTC. We similarly measured BD, SPR and saturated hydraulic conductivity (k_{fs}) in simulated tank tracks at another site near Lind Washington. Average BD was significantly greater in tank ruts at YTC and in simulated tracks at the Lind site than in uncompacted soil soon after tracking and did not change significantly during the winter of 1997–1998. Measurements of SPR were strongly influenced by soil moisture. When soil was moist or tracks were newly formed, SPR was significantly higher in tank ruts than in uncompacted soil from the surface to a depth of about 10–15 cm. The greatest average SPR in compacted soil was observed between 4 and 6 cm depth. We observed less difference in SPR between tank ruts and uncompacted soil near-surface at YTC as the time after trafficking increased. We observed highest SPR ratios (compacted rut:undisturbed) in fresh tracks near the surface, with lower ratios associated with increasing track age or soil depth, indicating that some recovery had occurred at YTC near-surface. However, we did not observe a similar over-winter change in SPR profiles at the Lind site. Rainfall simulator data from YTC showed higher steady-state runoff rates in tank ruts than over uncompacted soil both before and after winter. However, more time was required to reach steady-state flow in tank ruts and the proportion of runoff was slightly lower in May 1998 than in August 1997. At the Lind site,

* Corresponding author: Tel.: +1-304-256-2807; fax: +1-304-256-2971.
E-mail address: jjhalvorson@afsrc.ars.usda.gov (J.J. Halvorson).

k_{fs} was lower in newly compacted soil than in one-year old compacted soil or uncompacted soil. Our data suggest that indices of water infiltration such as steady-state runoff rates or k_{fs}, are more sensitive indicators of soil recovery after compaction than are BD or SPR. Published by Elsevier Ltd on behalf of ISTVS.

1. Introduction

Military training with tracked vehicles can disturb vegetation, form ruts, and compact soil, which can impact runoff and soil erosion on military lands such as Yakima Training Center (YTC) located in Washington State. Vegetation is directly impacted by maneuvers [15,20,28] and indirectly affected through changes in soil nutrient availability, soil physical characteristics, and patterns of soil moisture storage [5,7,14,35]. Tracking can destroy individual plants and alter community composition [2,3,4,19,31], or influence larger-scale patterns in the landscape [21] especially when combined with grazing, drought or fire.

Ruts can concentrate surface water flow, depending on orientation, slope, soil characteristics, and landscape position [11,33]. The geometry of hillslope channels, such as rills or ruts, is important because it influences the velocity and, thus, erosivity of water flowing in them [10,12]. Compacted soil in ruts affects erosion by changing the stability and size distribution of soil aggregates, and increasing soil bulk density and penetration resistance [12,16,30]. Small increases in soil bulk density can result in disproportionately large decreases in infiltration rates that increase the potential for runoff [22]. Rut geometry and the degree of compaction are influenced by vehicle factors and site factors [14,20,34]. Vehicle factors include contact area, surface pressure, weight, track slip, track design, vehicle speed, and driving pattern and the frequency and season of tank traffic. Site factors include soil characteristics such as texture, moisture, depth, and topography; plant characteristics, such as species composition, coverage, and growth stage; and climatic conditions, such as precipitation and temperature.

Once formed, compacted ruts are affected by environmental factors such as freeze-thaw cycles and wetting and drying [5,27,30]. Although the effects of soil compaction by tanks can persist for decades in some desert soils [23], data collected during 1996 in the shrub-steppe at the YTC demonstrate that significant changes (smoothing) in tank rut geometry can occur during a single year [16,17]. The data also suggest that soil is less compacted by tanks at the soil surface than deeper in the profile or, alternatively, that surface compaction does not persist. Less compaction may occur at the soil surface if water content is lower or if soil texture differs from that deeper in the profile. Alternatively, compacted soil near the surface may be more strongly affected by forces such as wind, and wetting-drying and freeze-thaw cycles that fluctuate with higher frequency and amplitude at the soil surface than deeper in the soil profile. Variation in the degree of compaction throughout the soil profile has important

implications for potential erosion and prediction because surface conditions do not necessarily represent the underlying soil.

This research is part of collaboration between the US Army Engineer Research and Development Center's Cold Regions Research and Engineering Laboratory and the United States Department of Agriculture, Agricultural Research Service to determine soil freeze-thaw effects on hydraulic geometry, soil strength, infiltration, runoff erosivity, and soil erodibility of vehicular ruts and natural rills. The objectives of this work were to study the short-term dynamics of change in soil compacted by tracked military vehicles. We measured indicators of compaction, such as soil bulk density, penetration resistance, steady-state runoff, and saturated hydraulic conductivity in soil soon after track formation and again after winter, to record amelioration of compaction over time. Changes in soil compaction are important to rut-flow hydraulics and erosion, and they can be readily measured by military land managers.

2. Approach

2.1. Study sites and methods

2.1.1. YTC

We studied tank ruts formed by one pass of M1A1 Abrams tanks during training maneuvers at YTC (Fig. 1). The YTC encompasses an area of over 130,000 ha and lies in shrub-steppe, the largest of the grassland regions in North America [26]. Soils are typically loess overlying basalt and the climate is characterized as semi-arid, temperate, and continental, with cold, wet winters and hot dry summers [4,25].

We concentrated our measurements in an area near Badger Gap (46° 50′ N 120° 16′ W; 700 m above sea level) where maneuvers in early spring 1997 had produced several parallel sets of tank ruts running east and west on a 1–5% slope in soil containing 20–25% water (by weight) in the 0–10-cm depth [8]. This area represents conditions common on the YTC, was accessible, had uniform vegetation and soil, and information about the time of rut formation and antecedent soil moisture was available. The soil here is classed as Benwy silt loam, a fine-loamy, mixed, super-active, mesic Calciargidic Argixeroll. Common vegetation in the area includes perennial native grasses such as blue-bunch wheatgrass (*Elytrigia spicata*) or Sandberg bluegrass (*Poa secunda*), sagebrush (*Artemisia tridentata* and *A. rigida*) and introduced annuals like tall tumble mustard (*Sisymbrium altissimum*) and cheatgrass (*Bromus tectorum*). Further details about this area are provided by [4].

To evaluate over-winter changes in the compacted tank-rut soil, we measured bulk density (BD) and soil penetration resistance (SPR) in the ruts and in adjacent, uncompacted soil lying within 1 m of the center of the ruts. We chose this distance because our previous work [17] indicated that effects of compaction during trafficking did not extend very far from the edge of tank ruts at YTC, and we wished to minimize the effects of natural spatial variability. We measured BD and SPR on 30 April 1997, about 1 month after tracking; on 5 November 1997, and on 21 April
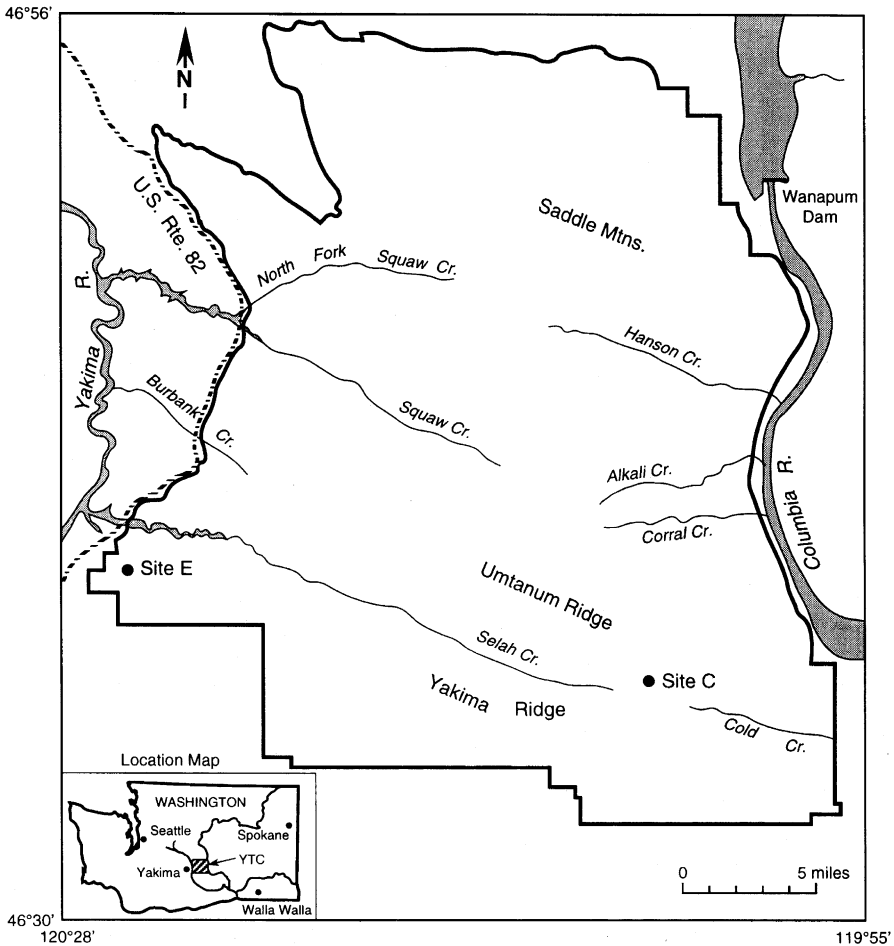
Fig. 1. Site map featuring an outline of Washington State with the locations of Yakima Training Center (YTC) and Lind shown. The YTC site is located at 46° 50′ N 120° 16′ W. The Lind site should be located at 46° 59′ N 118° 33′ W.

1998 (Table 1). On 14 March 1998, a portion of our research area was trafficked during M1 training maneuvers and we used this unplanned opportunity to compare SPR in ruts formed in April 1997 to new ruts only hours old. We sampled these new tracks for comparison to 1997 tracks again on 21 April 1998.

To measure BD, a hand-held coring device was pressed down into the soil surface to collect a 5-cm-diameter by 2.5-cm-deep core. Moisture content of the cores, corresponding to soil at a depth of 2.5–5 cm, was determined by the gravimetric method, and bulk density was calculated (dry mass per unit volume). We measured SPR using a hand-operated cone-type Bush recording soil penetrometer (Findlay, Irvine Ltd.), which measures the amount of pressure required to penetrate soil (e.g., [1,32]). The operator positioned the penetrometer perpendicular to the soil surface

Table 1
Sampling schedule at the Yakima Training Center

Sample date	Age of the tracks that were sampled	Variable(s) measured
30 April 1997	About 1 month old[a]	BD ($N = 5$), SPR ($N = 12$)
6–8 August 1997	About 4 months old[a]	Steady-state runoff
5 November 1997	About 7 months old[a]	BD ($N = 10$), SPR ($N = 22$)
14 March, 1998	Old tracks: about 1 year old[a]	SPR ($N = 22$)
	New tracks: about 1 day old[b]	SPR ($N = 24$)
21 April 1998	Old tracks: about 13 months old[a]	BD ($N = 10$), SPR ($N = 25$)
	New tracks: about 5 weeks old[b]	SPR ($N = 13$)
19–21 May 1998	About 14 months old[a]	Steady-state runoff

[a] Tracks were formed during tank-training maneuvers during late March–early April 1997.
[b] Tracks were formed during tank-training maneuvers on 14 March 1998.

and inserted it into the soil at a steady rate. For these measurements, we used a 7.9-mm-diameter cone and recorded the SPR data at 2-cm depth increments from 0, when the base of the cone tip was flush with the surface, to a depth of 16 cm, and stored the information in an onboard data-logger.

We measured steady-state runoff from tank ruts and adjacent uncompacted soil on 6–8 August 1997 and again on 19–21 May 1998 to assess changes in the impacts of soil compaction on rainfall infiltration and runoff with time. We applied rainfall with a rotating disk-type simulator previously developed to mimic the low intensity and small drop size rainfall typical of the Pacific Northwest [6] (Fig. 2a). Such rainfall simulators are useful for obtaining infiltration, runoff, and erosion data. Field-portable units are especially valuable because they allow control of the timing, amount, duration, and intensity of the rainstorm and thus make replication possible. To measure, we applied water at a constant rate (33 mm h^{-1}) onto paired 0.5×1.0 m bordered plots sunk in tank ruts or the adjacent uncompacted soil (Fig. 2b) and measured surface runoff as a function of time. The water used for the rainfall simulator experiments was obtained from a nearby well and of potable quality. It contained less than 16.7 mg/l sodium (Bob Corey, Directorate of Installation Service, YTC).

2.1.2. Lind

We also established three experimental plots at the Washington State University Dry-land Experiment Station (47° 0″ N 118° 33′ W; 465 m above sea level) located near Lind Washington. We selected this location because it had a climate and soil characteristics similar to YTC (Fig. 3) and was easier to access. The soil in the three plots is characterized as Roloff-Starbuck very rocky silt loams, taxonomically classified as coarse-loamy, mixed, superactive, mesic Aridic Haploxerolls and loamy, mixed, superactive, mesic Lithic Xerix Haplocambids. Plots A and B were vegetated with an overstory of large specimens of native sagebrush (*A. tridentata*) together with interstitial areas of cryptogamic crust, both indicative of a relatively undisturbed area [9]. Plot C was located nearby in slightly deeper soils in a area that had
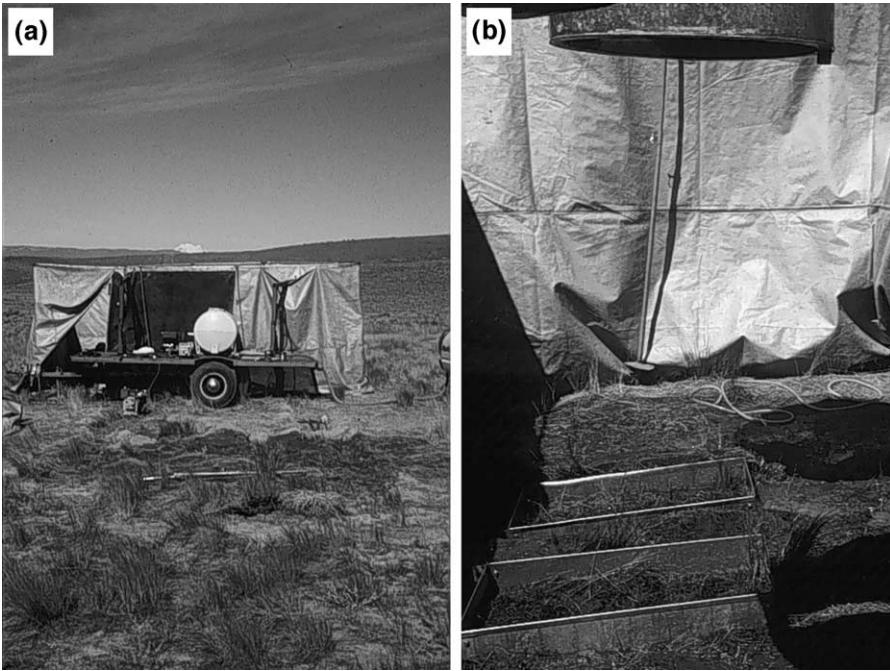
Fig. 2. (a) Rotating disk-type simulator developed to mimic the low intensity and small drop size rainfall typical of the Pacific Northwest, (b) applying about 33 mm h^{-1}.

been tilled and reseeded to grass mixture as part of the Conservation Reserve Program (CRP).

On 24 November 1997, we created a series of compacted imprints in each plot using a device designed to simulate track formation by M1A1 Abrams tanks. This apparatus, "Bigfoot," consisted of a single link of M1A1 tank tread, welded to a metal frame and equipped with a fitting (Fig. 4a). The fitting allowed us to attach Bigfoot to a Giddings hydraulic press mounted on a John Deere D350 caterpillar tractor (Fig. 4b). Using this setup, we were able to apply up to about 2141 kg of ground pressure. To simulate tracking, Bigfoot was positioned over the desired location and the track pad hydraulically pressed into the soil until the rear portion of the caterpillar tractor lifted off the ground. This procedure was applied twice to form each track location. At the time of tracking, soil moisture ranged from about 20–25% (by weight) in the 0–5 cm depth.

We measured BD and SPR in 15 track imprints (5 in each plot) on 25 November 1997 (Table 2) and again on 22 April 1998, and bulk density on 14 May 1998 in 15 different track imprints. On 19 November 1998, we added a series of fresh track imprints to plot C. On 4 December 1998, we measured saturated hydraulic conductivity (k_{fs}) in the fresh tracks (created November 1998), in older tracks (created November 1997) and in uncompacted soil in plot C to assess change in compacted soil with time ($N = 3$). We measured k_{fs} with a constant head pressure infiltrometer
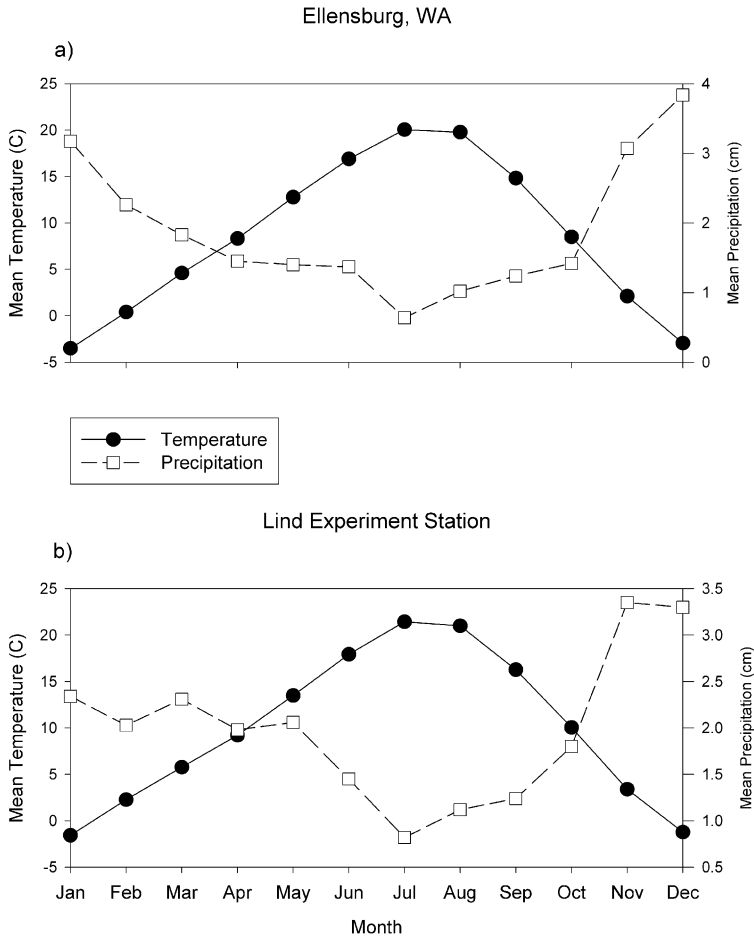
Fig. 3. Climate diagrams for National Climatic Data Center (NCDC) stations representative of (a) Badger Gap (near Ellensburg) and (b) Lind research areas. Monthly averages of temperature and precipitation were calculated from 30-year NCDC data (1961–1990). Average annual temperature and precipitation for Ellensburg was 8.5 °C and 22.7 cm., 9.8 °C and 23.8 cm for Lind.

(Soilmoisture Equipment Inc.) with a 10-cm ring and the approach and equations provided by [24]

$$k_{\mathrm{fs}} = \alpha^* \mathrm{GAR}_1 / \left[a(\alpha^* H_1 + 1) + G\alpha^* \pi a^2 \right] \tag{1}$$

Where α^* is a soil texture structure parameter (0.12 cm^{-1} for most structured soils); A is the cross-sectional area of the infiltrometer reservoir (2.18 cm^2 for our readings); R_1 (cm s^{-1}) is the steady rate fall of the water level in the infiltrometer reservoir; a is the inside radius of the soil ring (5 cm); H_1 is the steady pressure head on the infiltration surface (10 cm); and G is a dimensionless shape factor (0.5 for our measurements).
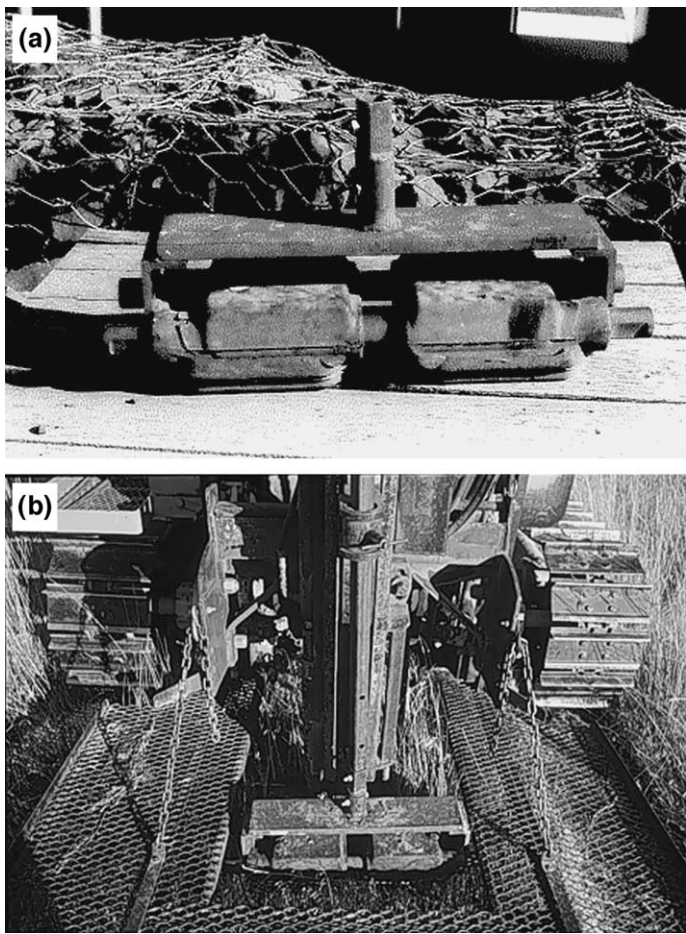
Fig. 4. Details of (a) the 'Bigfoot' apparatus, (b) mounted for compaction of soil.

Table 2
Sampling schedule at Lind Washington

Sample date	Age of the tracks that were sampled	Variable(s) measured
25 November 1997	About one day old[a]	BD ($N=15$), SPR ($N=15$)
22 April 1998	About 5 months old[a]	SPR ($N=15$)
14 May, 1998	About 6 months old[a]	BD ($N=15$)
4 December 1998	Old tracks: about 1 year old[a]	k_{fs} ($N=3$)
	New tracks: about 2 weeks old[b]	

[a] Tracks were formed with the "Bigfoot" apparatus on 24 November 1997.
[b] Tracks were formed with the "Bigfoot" apparatus on 19 November 1998.

2.2. Statistical analysis

We analyzed BD data for YTC and Lind sites with a 2-way analysis of variance (ANOVA) to determine if there were significant differences between compacted and uncompacted soil or significant change over time. We chose this approach rather than a repeated measures analysis because we could not sample the identical locations each time. We constructed plots of average SPR values (with 95% confidence intervals) as a function of soil depth for each sample date and used paired t-tests to determine if there was a significant difference between compacted and uncompacted soil or among different depths. We used a simple one-way ANOVA, and its nonparametric analog, the Kruskal–Wallis test, to determine if there were significant differences in k_{fs} among new-tracked, old-tracked, or uncompacted locations at the Lind site. Differences in paired t-tests or ANOVA analyses were considered significant if the Bonferroni adjusted probabilities were $\leqslant 0.05$. All statistics were calculated using Systat [29].

3. Results and discussion

3.1. Bulk density and soil moisture

Average BD was significantly greater in tank-compacted soil than in uncompacted soil, at YTC, by more than 14.5% but did not differ significantly among the three sample dates ($P = 0.1$) (Fig. 5a). Conversely, average soil H_2O was unaffected by soil compaction ($P = 0.66$) but the soil contained significantly more water in April and November 1997, 16.8 and 16.9% by weight, than in April 1998, 10.8% (Fig. 6a). Like YTC, average BD at the Lind site was significantly higher in locations compacted by the Bigfoot apparatus than in adjacent uncompacted soil by almost 6% but did not change significantly between November 1997 and May 1998 ($P = 0.12$) (Fig. 5b). The average value of soil H_2O did not differ significantly between compacted and uncompacted soil at the Lind site but was two times greater in November 1997 (24.1%) than in May 1998 (12.1%) (Fig. 6b).

3.2. Soil penetration resistance

Soil penetration resistance at YTC varied significantly with depth and between compacted and uncompacted soil when measured on 30 April 1997, about one month after tracking (Fig. 7a). Because of surface soil drying and looseness, the Bush recording soil penetrometer was unable to consistently record values for SPR at the soil surface in tank ruts or uncompacted soil. However, below that, average SPR, in uncompacted soil, increased significantly with depth to about 1.5 MPa at 16 cm depth. Soil penetration resistance in tank ruts increased with depth to about 2.5 MPa at 6 cm, but then decreased to values identical with those of uncompacted soil at 16 cm depth. Average SPR in tank ruts was significantly greater than in uncompacted soil at depths between 2 and 10 cm.
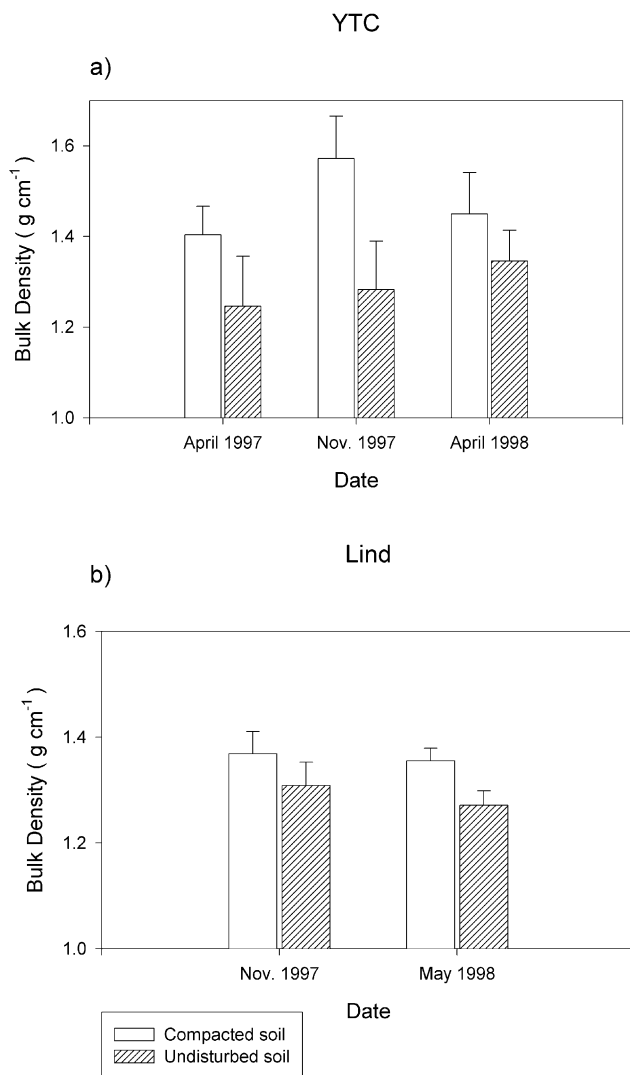
Fig. 5. Average bulk density and 95% Confidence intervals for (a) Yakima Training Center and (b) Lind sites. Samples for YTC were collected on 30 April 1997 ($N = 5$), 5 November 1997 ($N = 10$), and on 21 April 1998 ($N = 10$). Samples were collected at Lind on 25 November 1997 and 14 May 1998 ($N = 15$).

We observed significant differences in SPR between tank ruts and uncompacted soil and among different depths on 5 November 1997 (Fig. 7b). As in April, average SPR in uncompacted soil was low at the surface and increased to a value of about 1.5 MPa at 16 cm depth. Average SPR in tank ruts increased significantly with depth, from about 0.9 MPa at the surface to nearly 2.0 MPa at 4 cm depth and was significantly greater in tank ruts than in uncompacted soil from the surface to a depth of about 12 cm.
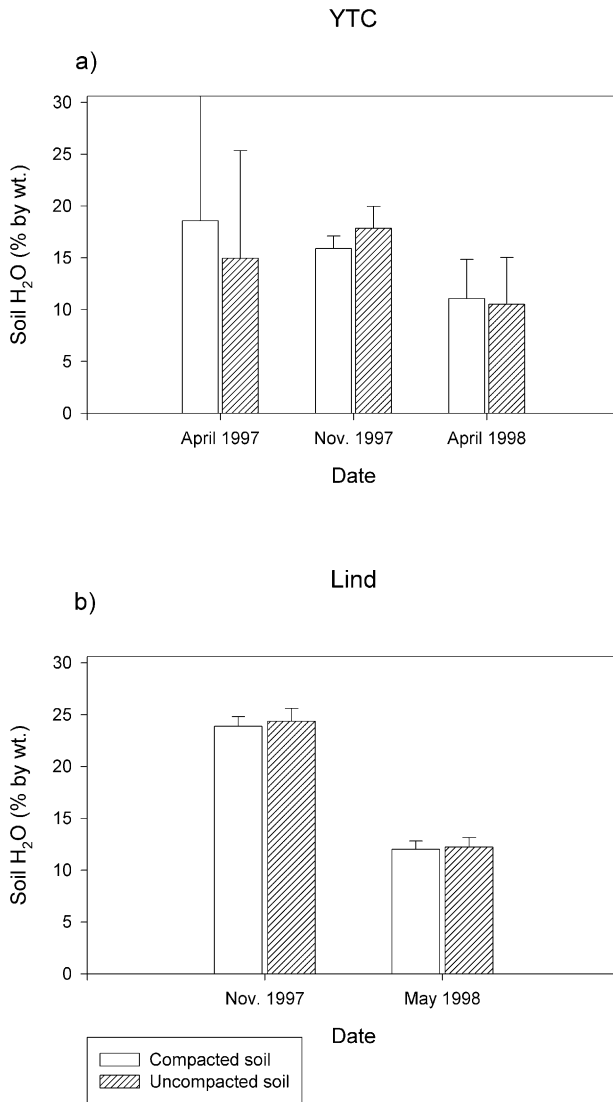
Fig. 6. Average soil moisture, shown with 95% confidence intervals, for (a) Yakima Training Center and (b) Lind sites. Samples for YTC were collected on 30 April 1997 ($N = 5$), 5 November 1997 ($N = 10$), and on 21 April 1998 ($N = 10$). Samples were collected at Lind on 25 November 1997 and 14 May 1998 ($N = 15$).

Comparing data collected in November 1997 to those collected the previous April (Fig. 7a and b) illustrates the sensitivity of SPR measurements to variation in moisture in the soil profile. While moist soils are easier to penetrate than dry soils, and result in comparatively lower, more consistent SPR readings, soil moisture may not be distributed evenly with depth. November SPR data were collected in soil
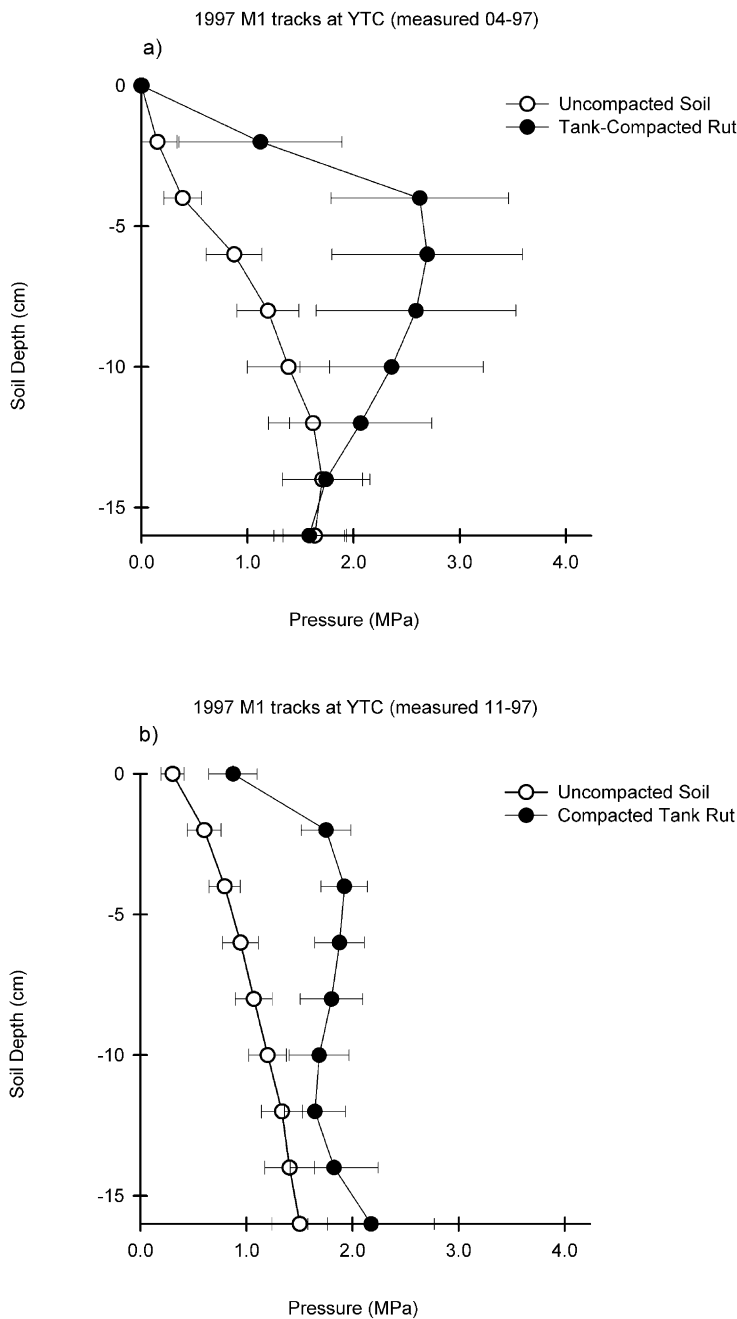
Fig. 7. Average soil penetration resistance (+/- 95% confidence intervals) for uncompacted (open circle) and tank-compacted soil (closed circle) at Yakima Training Center on (a) 30 April 1997 about 1 month after tracking (*N* = 12); (b) 5 November 1997 (*N* = 22); (c) on 14 March 1998 (*N* = 22); and (d) 21 April 1998 (*N* = 25).
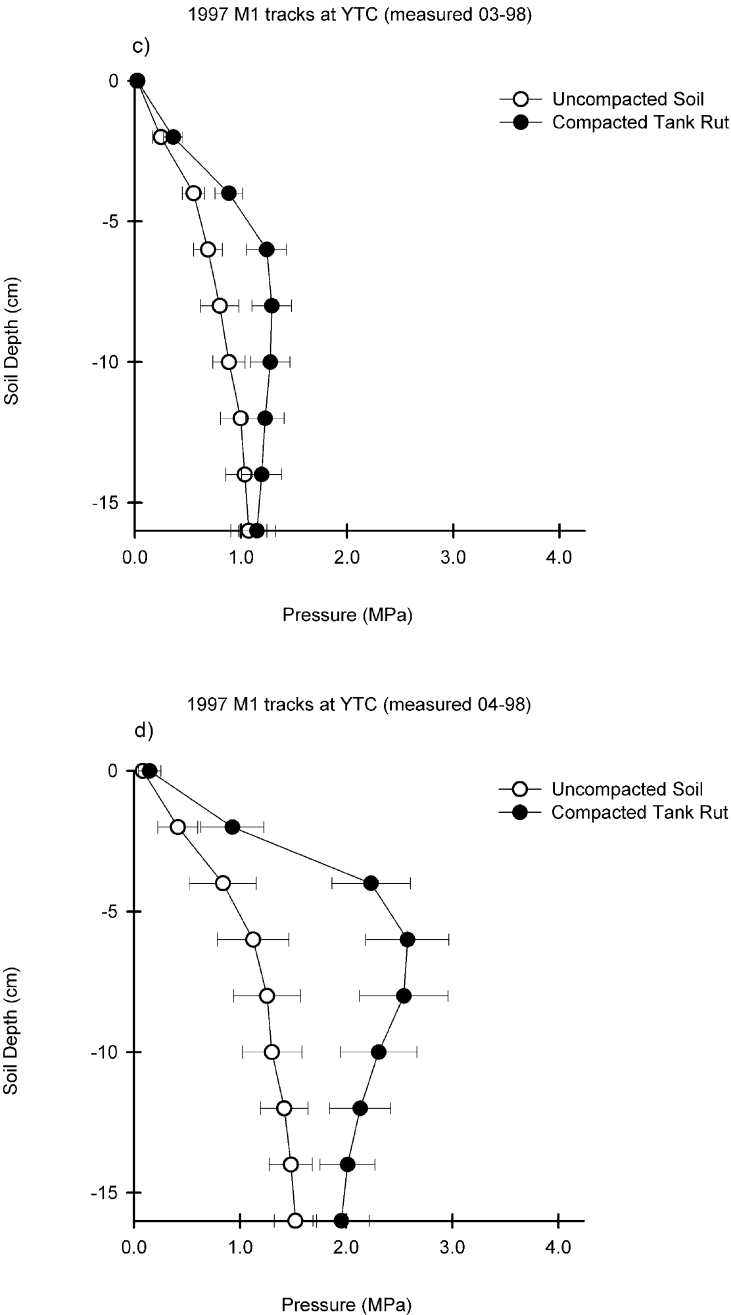
Fig. 7. (*continued*)

immediately after rain, at the beginning of the winter precipitation cycle (see Fig. 3). While the soil was clearly wet near the surface (Fig. 6), below about 12 cm, SPR in ruts increased significantly, corresponding to drier soil below the wetting front (measured at 15–17 cm by hand excavation). In contrast, we did not observe the same sort of dry soil or a similar corresponding increase in SPR in uncompacted soil. Our earlier observations indicate that soil compacted by a tank can have a reduced saturated hydraulic conductivity relative to adjacent untrafficked soil ([17]). While a moist, rain-compacted soil surface in November may help explain the significantly higher SPR in both ruts and uncompacted soil near the surface compared to the previous April, when the soil surface appeared dry, consistent measurement of SPR at the surface is complicated by other soil conditions besides moisture.

Like spring 1997, average soil surface SPR was below detection for uncompacted soil or ruts on 14 March 1998 (Fig. 7c). Average SPR increased significantly with depth to a maximum value near 1 MPa at 16 cm and near 1.1 MPa at 8 cm in uncompacted soil and ruts respectively. Average SPR was significantly greater in ruts than in uncompacted soil at depths between 4 and 12 cm.

Data collected on 21 April 1998, in now 1-year-old ruts, were similar to those recorded in April 1997, shortly after tracking (Fig. 7d). Average SPR increased significantly with depth in uncompacted soil, ranging from undetectable levels at the surface to an average value of about 1.5 MPa at 16 cm. Average SPR in ruts also increased significantly with depth, reaching a maximum value of about 2.6 MPa at 6 cm then decreasing significantly to about 2.0 MPa. Average SPR was significantly greater in ruts than in uncompacted soil at depths greater than 2 cm.

Tank training maneuvers on 14 March 1998 across our study area created a serendipitous opportunity to compare newly created ruts to those created the previous year. In these new ruts, average SPR increased significantly with depth in uncompacted soil to an average value near 1.4 MPa at 16 cm (Fig. 8a). Average SPR in ruts increased significantly with depth to an average value near 1.2 MPa at 4 cm, but remained constant at greater depths. Even though surface values were very low, average SPR was significantly greater in new tank ruts than in uncompacted soil from the soil surface to about 10 cm. The average SPR profile in the top 10 cm of uncompacted soil near new ruts was not significantly different from that near older ruts (compare Fig. 8a with Fig. 7c). In comparison, the average SPR values were significantly greater in the top 4 cm of new tank ruts compared to older ruts, but identical at greater depths.

We measured SPR in these new ruts again on 21 April 1998. Average SPR increased with depth in uncompacted soil to an average value near 1.4 MPa at 16 cm (Fig. 8b). Average SPR in new ruts increased significantly to highest values of 3.2 MPa at 2 cm, and then declined significantly with depth to 1.5 MPa at 16 cm. The average SPR was significantly greater in tank ruts than in uncompacted soil from the surface to about 8 cm. The average SPR profile in uncompacted soil near new ruts was not significantly different from that near older ruts (compare Fig. 8b with Fig. 7d). However, average SPR values in new 1998 tank ruts were significantly greater in the top 4 cm and significantly less at depths below 10 cm than in older ruts.

The opportunity to compare SPR measurements that were collected simultaneously from newer and older ruts was valuable for distinguishing those changes in
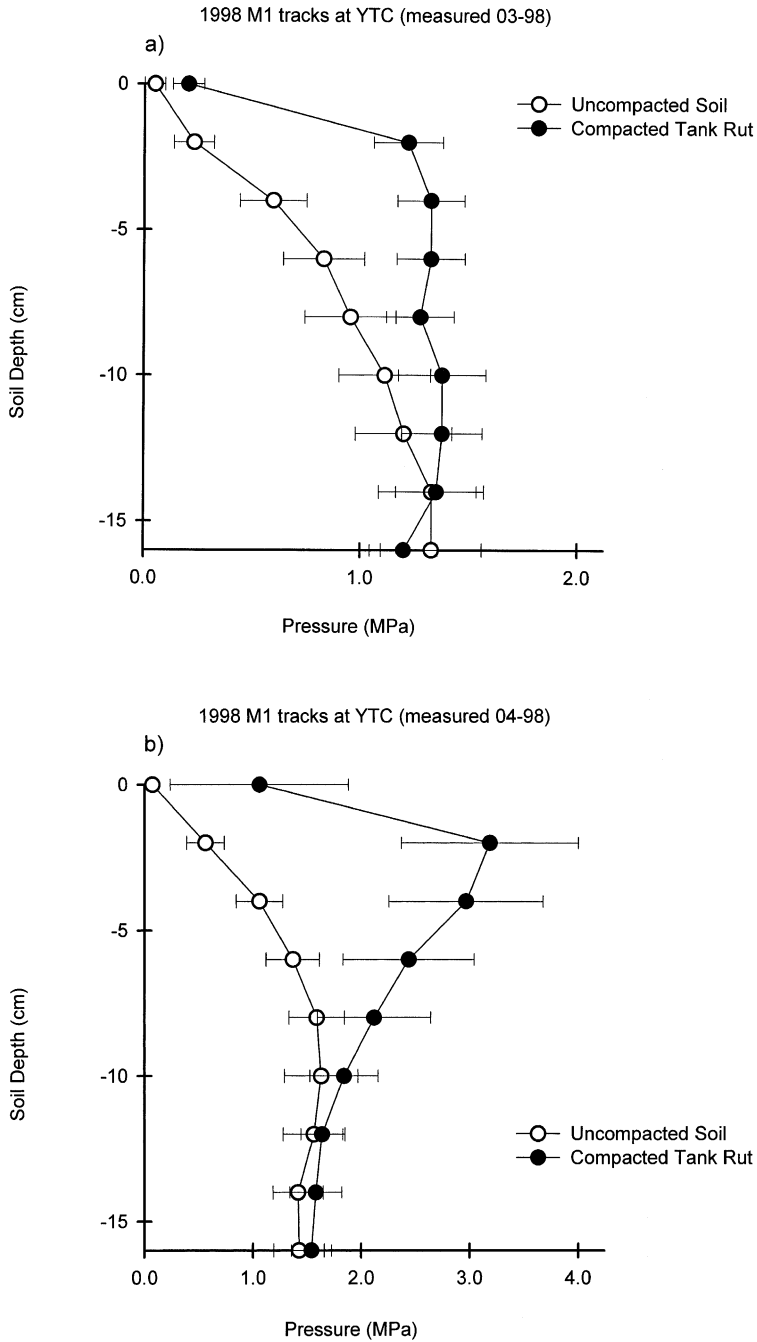
Fig. 8. Average soil penetration resistance ($+/-$ 95% confidence intervals) for uncompacted (open circle) and tank-compacted soil (closed circle) at Yakima Training Center on a) on 14 March 1998, the day of tracking ($N=24$) and b) 21 April 1998 ($N=13$). Note different scales.
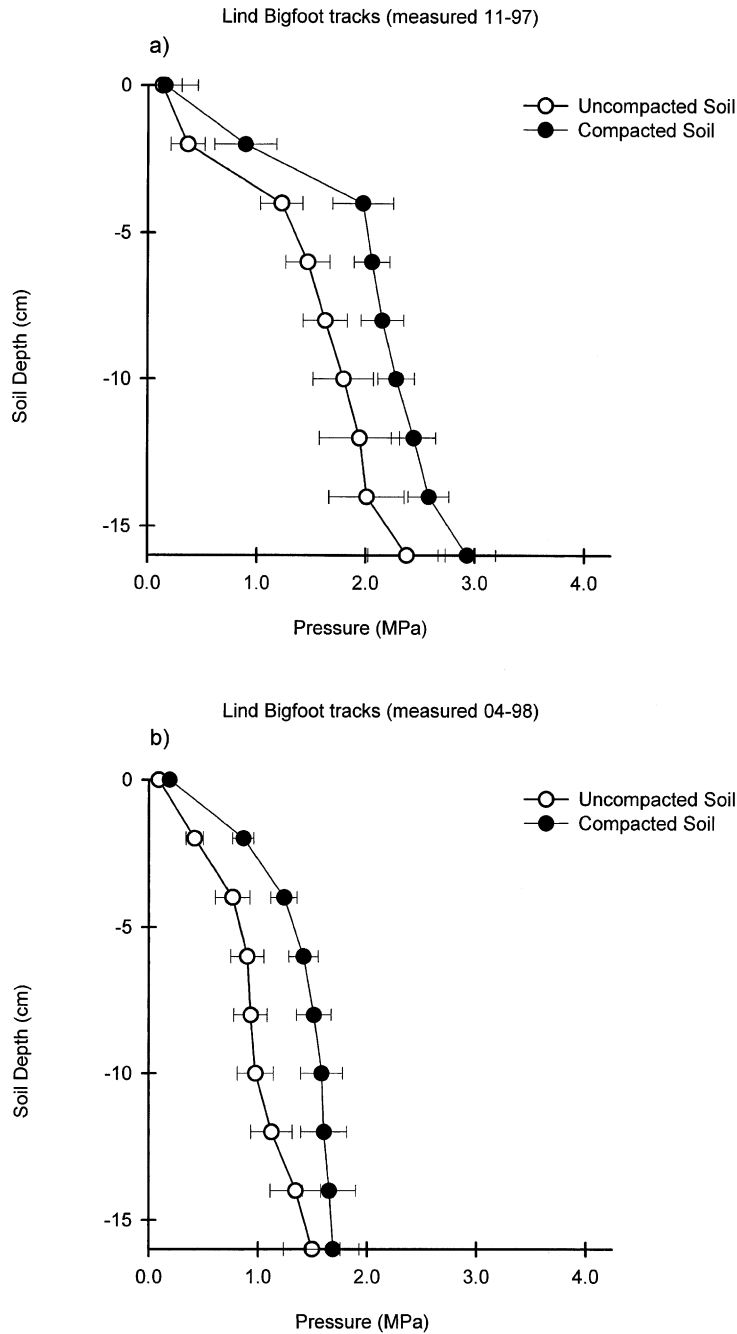
Fig. 9. Average soil penetration resistance ($+/-$ 95% confidence intervals) for uncompacted (open circle) and compacted soil (closed circle) at Lind on (a) on 25 November 1997, the day of tracking and (b) 22 April 1998 ($N = 15$).

SPR attributable to amelioration of soil compaction from changes in SPR related to variations of soil moisture. In March and April 1998, we observed significantly greater SPR in the top 4 cm of new ruts than in 1-year-old ruts with a correspondingly smaller difference between tracked and untracked soil (compare Fig. 7c to Fig. 8a and Fig. 7d with Fig. 8b). Data collected in April 1998, from newly tracked locations (tracks about 2 weeks old), showed much greater differences between tracked and untracked soil near the surface than the 1-year-old tracks.

In general, the highest average SPR values recorded for tank ruts were associated with more sample variability than in the corresponding uncompacted soil (e.g. Fig. 7a), an observation also reported by [23] who suggested this could be caused by the tendency of tanks to bounce considerably when traveling across undulating terrain or that variations in soil moisture content at the time of impact can affect degrees of soil compaction. Average SPR values were lower and less variable in November after the beginning of the winter wet season (see Fig. 3a) and especially in March when soil H_2O in the sample area was about 27.5% in the top 5-cm of soil and close to 20% at depths between 5 and 25 cm than 1 month later, in April 1998, when soil moisture was lower (10.8%) near the surface. The decrease in soil moisture between March and April can be attributed to complete thawing and drainage of the soil or evapotranspiration resulting from growing vegetation, increasing temperatures or by drying by seasonal winds (Brian Cochrane YTC personal observation).

The pattern of SPR observed at Lind was comparable to that seen at YTC. From undetectable levels at the surface, average SPR increased with depth to a value near 2.3 MPa at 16 cm in uncompacted soil (Fig. 9a). Compacting the soil with the Bigfoot apparatus on 25 November 1997 significantly increased SPR below the soil surface. Average SPR in Bigfoot imprints increased to about 2 MPa at 4 cm depth and then increased more gradually to 2.9 MPa at 16 cm. Average SPR did not change at the surface or 2-cm depth between tracking in November and April. At other depths, SPR in both compacted and uncompacted soil was higher in November than in April.

The M1A1 battle tank, with an estimated vehicle weight of about 63,000 kg (69.5 tons), exerts an average static ground pressure of 1.08 kg/cm^2 (15.4 psi) [13]. In contrast, we measured a total vehicle mass for the 'Bigfoot' apparatus of only 2121 kg. However, owing to the relatively small area of the two tread pads in contact with the ground (676.2 cm^2), Bigfoot was capable of exerting nearly three times the average ground pressure, 3.16 kg/cm^2 (45.0 psi), as the tank. Despite this, we recorded comparatively low average SPR values and no significant difference between compacted and uncompacted surface soil at the Lind site on the day of tracking. Similarity between SPR measurements, for compacted and uncompacted soil at the soil surface, may be the result of instrument limitations related to measuring at the surface (see below), as the surface depth reading is recorded when the base of the penetrometer cone tip is at the soil surface. Another potential contributing factor might be a relatively dry soil surface or a particle size distribution that would resist soil compaction. During the excavation of soil cores for BD measurements at the Lind site, we observed a 2- to 3-cm-thick layer of relatively coarse volcanic ash, from the 1980 eruption of Mount St. Helens, near the soil surface.

3.3. SPR ratios

The cone penetrometer is a useful field tool: measurements can be made quickly, it's simple to operate, and it can be used to collect a depth profile of SPR. However, penetrometer readings, which are an integrated measure of soil strength, are affected by several soil properties including soil BD, texture, and water content at the time of measurement [5]. If surface soil particle size distributions differ greatly from those at depth or if the soil surface is loose and friable, crusted, or rough, SPR readings may appear undetectable or highly variable between samplings. To aid comparisons, we used the ratio calculated with compacted and uncompacted SPR data for each depth below 2 cm to account for small-scale spatial variability of soil properties among sample locations and variation in soil moisture at different sampling dates.

We observed the highest SPR ratios near the soil surface, at YTC, in young ruts and lower ratios in ruts of increasing age or with depth (Fig. 10a). At 2 cm depth, 1-month-old M1 ruts at YTC had an SPR ratio of 7.5 in April 1997, while ratios of 5.3 and 5.7 were recorded for 1998 M1 ruts, 1 day and 5 weeks old, respectively. After 8 months, ruts formed in spring 1997 at YTC had an SPR ratio, at 2 cm, of 2.9, but only about 1.5 by the time the ruts were 13 months old. The SPR ratios observed in ruts of all ages decreased with soil depth to less than 1.5 at 16 cm depth.

We observed a similar, though less pronounced, pattern for the SPR ratios in the ruts made at Lind (Fig. 10b). The largest ratios were observed near the soil surface, 2.4 in fresh Bigfoot tracks in November or about 18% greater than those for the same tracks in April. Ratios decreased with depth to values less than 1.25 at 16 cm. The patterns of SPR ratios observed at both sites suggest that the greatest relative increases in soil compaction due to tracking occur within about 5 cm of the soil surface, which is also the zone where the greatest changes in soil compaction were recorded (Fig 10a). In undisturbed locations soil compaction, BD and SPR tend to increase with depth, in part, because of the mass of the overlying soil [18]. Compacted soil near the surface is not influenced by overburden and is also more strongly affected by cycles of freezing and thawing, drying and wetting or the actions of soil biota. Higher SPR ratios in young ruts, compared to older ruts, indicate that changes of soil compaction occur relatively rapidly, in agreement with [30], who reported recovery of the soil structure, vegetation cover, and standing crop in M2 Bradley tracks after only 2 years, to the point that there was no longer any significant influence on infiltration rate or inter-rill erosion. However, some combinations of soil, climate, and tracking patterns appear to resist recovery, [23] found 50% more penetration resistance in the upper 20 cm of Mojave Desert soil 40 years after tracking by tanks.

3.4. Steady-state runoff

Soil compaction by M1 tanks affected the timing and amount of runoff during runs of the rainfall simulator. On 6–8 August 1997, about 4 months after tracking, the average steady state runoff (percentage of total water applied) in tank ruts was about 75% of the water application rate (average 33 mm h^{-1}) compared to about
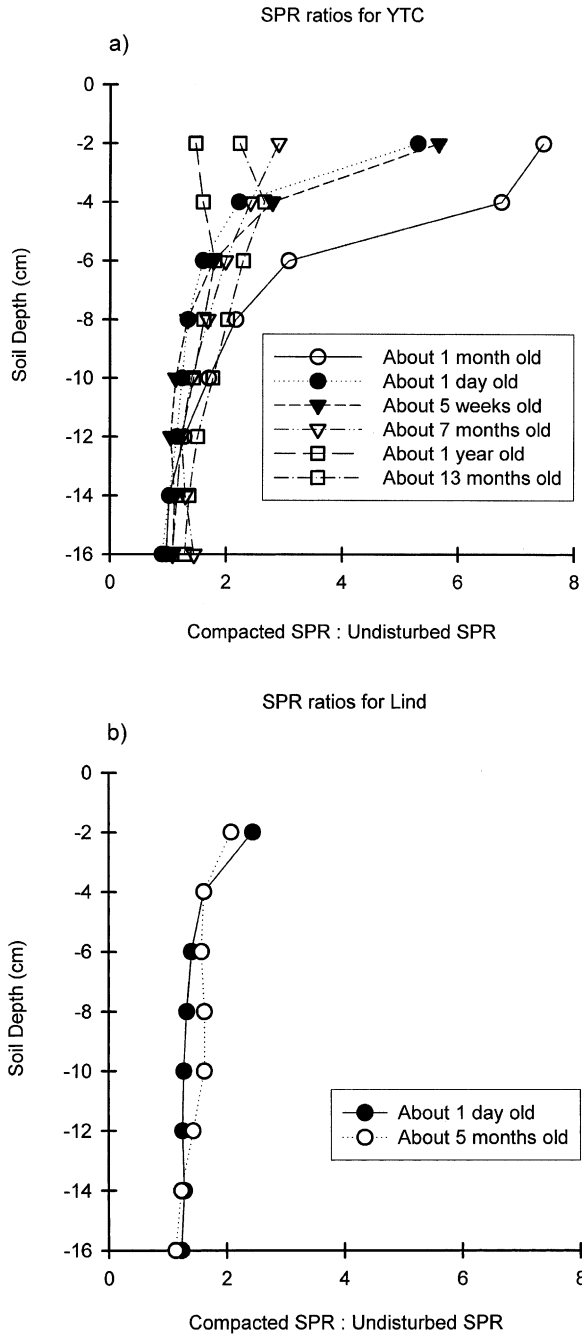
Fig. 10. Soil penetration resistance ratios as a function of depth for (a) Yakima Training Center and (b) Lind. The legend indicates the amount of time between track formation (open symbols in Fig. 10a indicate spring 1997, filled symbols, spring 1998) and SPR measurements. Ratios from the soil surface are not shown.
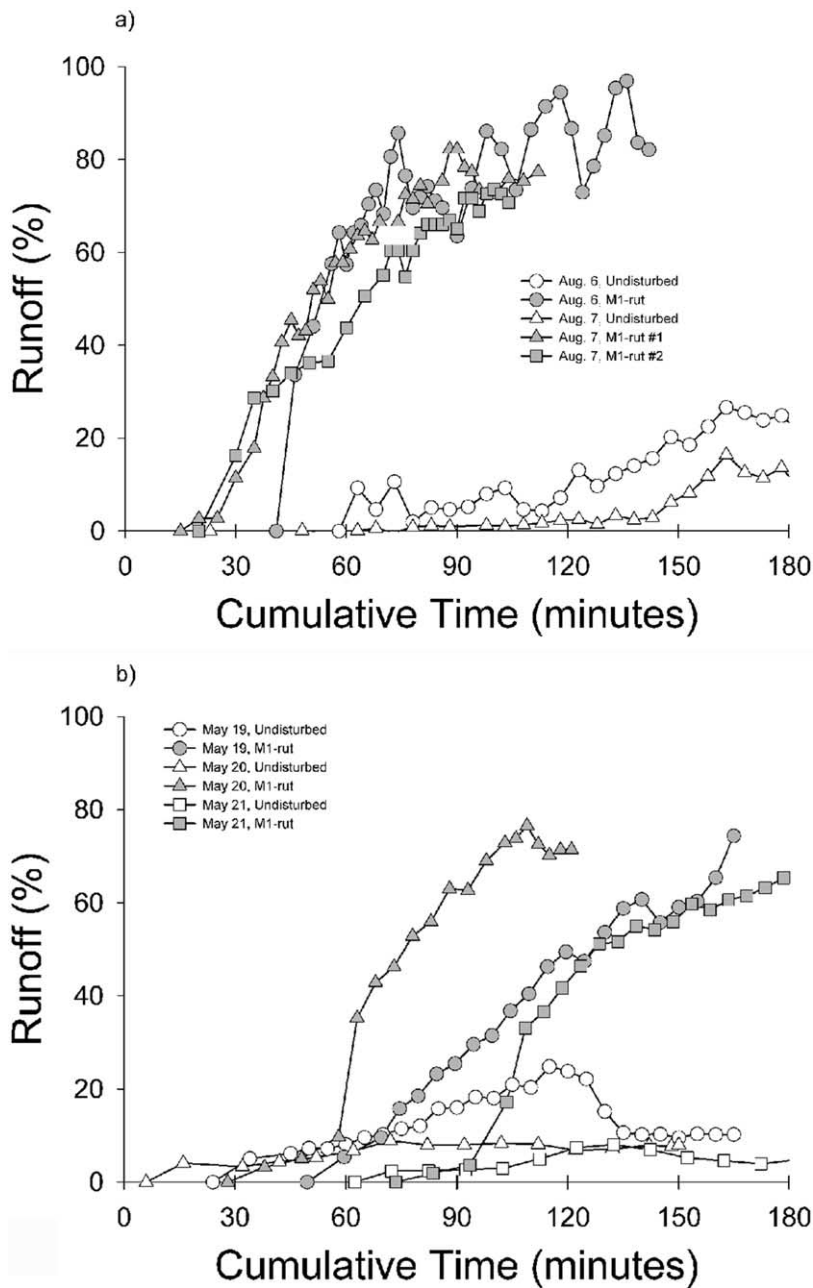
Fig. 11. Rainfall simulator plot runoff (% of total water applied) as a function of time for (a) 6–8 August 1997 and (b) 19–21 May 1998.

19% for uncompacted soil (Fig. 11a). It took about 90 min to reach steady-state flow in tank ruts but almost twice as long in uncompacted soil. In comparison, average steady-state runoff rates in both tank ruts and uncompacted soil were slightly lower in May 1998, 66 and 8%, respectively (Fig. 11b). There was more variability in the final runoff rates and in the amount of time needed to reach these rates among individual tank ruts measured in May than the previous August. Two of three tank ruts measured did not approach steady-state runoff until about 150 min of simulated rainfall, the same time needed for uncompacted soil. Average depth to the wetting front in the soil of tank ruts was 21.2 cm compared to 46.7 cm in uncompacted soil in May 1998.

3.5. Saturated hydraulic conductivity

Saturated hydraulic conductivity in Lind soil was significantly decreased by compaction with the Bigfoot apparatus and the effects of compaction appeared to diminish significantly with time (Fig. 12). We recorded the lowest average k_{fs} in tracks about 2 weeks old, 2.5×10^{-4} cm sec^{-1}, similar to that measured in 1-year-old tracks, 3.6×10^{-4} cm s^{-1} ($P = 0.72$), but significantly less than that found in uncompacted soil, 5.1×10^{-4} cm s^{-1} ($P = 0.05$). Though lower, the average k_{fs} in old Bigfoot tracks could not be distinguished from uncompacted soil ($P = 0.31$). We corroborated these results with a Kruskal–Wallis nonparametric test, selected to relax the assumptions about the distribution of the data, because measurements of k_{fs} were more variable in newly compacted soil than older compacted or uncompacted soil, with coefficients of variation of 53, 14, and 18%, respectively.
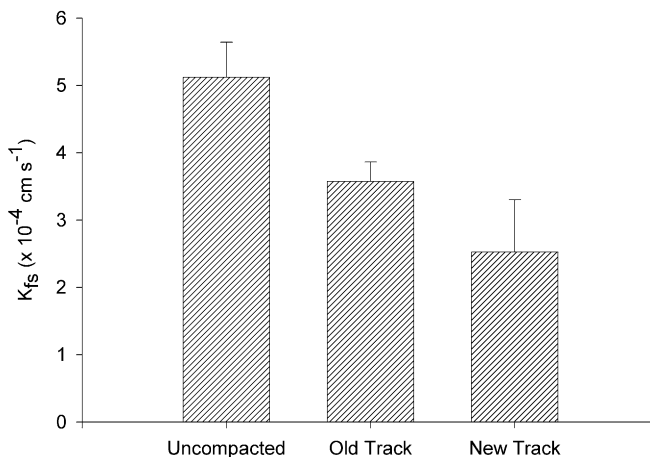

Fig. 12. Average saturated hydraulic conductivity (k_{fs}) (+/- standard error) for uncompacted soil and "Bigfoot" tracks about 1-year (old) or about 2-weeks (new) old. ($N = 3$).

4. Conclusions

Our data indicate that BD was significantly increased in tank ruts at YTC and in simulated tracks at Lind but did not undergo an appreciably change over winter. Similarly, SPR was significantly greater in compacted soil than uncompacted soil with differences between the two most pronounced near the surface. Soil penetration resistance measurements are strongly influenced by amount of moisture in the soil at the time of measurement, but SPR ratios allowed us to compare samples collected at different dates and moisture conditions. These ratios indicate that both the greatest relative compaction and recovery occur near the soil surface and can be detected within a year after tracking. Little overwinter recovery was detected below about 5 cm. Measurements of steady-state runoff from simulated rainfall at YTC and comparisons of k_{fs} in compacted soils of different ages at the Lind site also indicate that significant recovery can occur in compacted soil following a single winter season, even when it was not detectable by other indices of compaction such as BD and SPR. These data suggest that changes in the rate of water infiltration are more sensitive indicators of amelioration of soil compaction than are bulk density or penetration resistance.

References

[1] Anderson G, Pidgeon JD, Spencer HB, Parks R. A new hand-held recording penetrometer for soil studies. Journal of Soil Science 1980;31:279–96.

[2] Bern CM. 1996a. Land condition-trend analysis, field report 1989–1994: Yakima Training Center, Washington. Colorado State University, Fort Collins, CO: Center for Ecological Management of Military Lands, TPS 96-7.

[3] Bern CM. 1996b. Land condition-trend analysis, field report 1996: Yakima Training Center, Washington. Colorado State University, Fort Collins, CO: Center for Ecological Management of Military Lands, TPS 96-11.

[4] Bern CM. 1998. Land condition-trend analysis, field report 1997: alkali and corral canyons following the fire of 1996, Northern Expansion Area, Yakima Training Center, Washington. Colorado State University, Fort Collins, CO: Center for Ecological Management of Military Lands, TPS 98-2.

[5] Braunack MV. The residual effects of tracked vehicles on soil surface properties. Journal of Terramechanics 1986;23:37–50.

[6] Bubenzer GD, Molnau M, McCool DK. Low intensity rainfall with a rotating disk simulator. Transactions of the American Society of Agricultural Engineers 1985;28:1230–2.

[7] Buchkina NP. Impacts of tracked vehicles on properties of tundra soils. In I.K. Iskandar et al., (Eds.) Proceedings of the International Symposium on Physics, Chemistry, and Ecology of Seasonally Frozen Soils, Fairbanks, Alaska, 10–12 June (pp. 473–476). 1997. U.S. Army Cold Regions Research and Engineering Laboratory, Special Report 97-10.

[8] Cochrane B. 1998. Soil moisture monitoring in support of Cascade-Sage 1997, Yakima Training Center, Yakima, Washington. Special report to YTC.

[9] Daubenmire R. 1970. Steppe vegetation of Washington. Washington Agricultural Experiment Station, College of Agriculture, Washington State University, Pullman, WA Technical Bulletin 62. 1970.

[10] Elliot WJ, Laflen JM. A process-based rill erosion model. Transactions of the American Society of Agricultural Engineers 1993;36:65–72.

[11] Folz RB. 1993. Sediment processes in wheel ruts on unsurfaced forest roads. PhD dissertation, University of Idaho.

[12] Gatto LW. Ground freezing effects on soil erosion of army training lands. Part 1: initial test results. US Army Cold Regions Research and Engineering Laboratory, Special Report 97-15.1997.

[13] General Dynamics. General Dynamics Land Systems home page. URL: http://www.gdls.com/ 1997.

[14] Goran WD, Radke LL, Severinghaus WD. 1983. An overview of the ecological effects of tracked vehicles on major US army installations. US Army Construction Engineering Research Lab, Technical Report N-142.U.S. Champaign, IL: Army Corps of Engineers.

[15] Greene TA, Nichols TJ. Effects of long-term military training traffic on forest vegetation in central Minnesota. Northern Journal of Applied Forestry 1996;13:157–63.

[16] Halvorson, JJ, McCool DK, King LG, Gatto LW. Ground freezing effects on soil erosion of army training lands. Part 2: overwinter changes to tracked vehicle ruts, Yakima Training Center, Washington. USA Cold Regions Research and Engineering Laboratory, Special Report 98-8. 1998.

[17] Halvorson JJ, McCool DK, King LG, Gatto LW. Overwinter changes to tracked vehicle ruts, Yakima Training Center, Washington. Journal of Terramechanics 2001;38:133–51.

[18] Hartge KH. 1998. The reference base for compaction state of soils. In Drescher, J. R. Horn, and M. de Boodt (Eds.), Impact of water and external forces on soil structure: selected papers of the 1st workshop on soilphysics [sic] and Soilmechanics [sic]. Catena supplement 11, Cremlingen-Destedt, pp. 73–77.

[19] Jones DS, Bagley CF. 1997. Tracked military vehicle impacts on three vegetation communities at Yakima Training Center, Washington: results for the 1994–1996 study period. Center for Ecological Management of Military Lands; Colorado State University: TPS 97-4.

[20] Jones DS. 1998. Experimental approaches for measuring tactical vehicle impacts. Presentation at the Seventh Annual DA-ITAM Workshop, 25–28 August 1998 Yakima WA.

[21] Knick ST, Rotenberry JT. Landscape characteristics of disturbed shrubsteppe habitats in southwestern Idaho (U.S.A.). Landscape Ecology 1997;12:287–97.

[22] Meek BD, Rechel ER, Carter LM, DeTar WR. Bulk density of a sandy loam: traffic, tillage, and irrigation-method effects. Soil Science Society of America Journal 1992;56:562–5.

[23] Prose DV. Persisting effects of armored military maneuvers on some soils of the Mojave Desert. Environ Geol Water Sci 1985;7:163–70.

[24] Reynolds WD. Saturated hydraulic conductivity: field measurement. In: Carter MR, editor. Soil sampling and methods of analysis. Lewis Publishers: Canadian Society of Soil Science; 1993. p. 599–613.

[25] Rickard WH. Climate of the Hanford Site. In: Rickard WH, et al., editors. Shrub-steppe, balance and change in a semi-arid terrestrial ecosystem. New York: Elsevier; 1988. p. 13–21.

[26] Rogers LE, Rickard WH. Introduction: Shrub-steppe lands. In: Rickard WH, et al., editors. Shrub-steppe, balance and change in a semi-arid terrestrial ecosystem. New York: Elsevier; 1988. p. 1–12.

[27] Sharratt BS, Voorhees W, McIntosh G. 1997. Amelioration of soil compaction by freezing and thawing. In I.K. Iskandar et al., (Eds.), Proceedings of the International Symposium on Physics, Chemistry, and Ecology of Seasonally Frozen Soils, Fairbanks, Alaska, 10–12 June 1997 (pp. 182–188). US Army Cold Regions Research and Engineering Laboratory, Special Report 97-10:1997:182–188.

[28] Shaw RB, Diersing VE. Tracked vehicle impacts on vegetation at the Pinon Canyon Maneuver site, Colorado. Journal of Environmental Quality 1990;19:234–43.

[29] SPSS Inc. (1998). Systat. SPPS Inc., Chicago, IL.

[30] Thurow TL, Warren SD, Carlson DH. Tracked vehicle effects on the hydrologic characteristics of central Texas rangeland. Transactions of the American Society of Agricultural Engineers 1993;36: 1645–50.

[31] Trame A, Harper M. Potential military effects on selected plant communities in the Southeastern United States. USACERL Technical Report 97/115. 1997.

[32] Vazquez LD, Myhre L, Hanlon EA, Gallaher RN. Soil penetrometer resistance and bulk density relationships after long-term no tillage. Communications in Soil Science Plant Analysis 1991;22: 2101–17.

[33] Voorhees WB, Young RA, Lyles L. Wheel traffic considerations in erosion research. Transactions of the American Society of Agricultural Engineers 1979;22:786–90.

[34] Wilson SD. The effects of military tank traffic on prairie: a management model. Environmental Management 1988;12:397–403.

[35] Wolkowski RP. Relationship between wheel-traffic-induced soil compaction, nutrient availability, and crop growth: a review. Journal of Production Agriculture 1990;3:460–9.